

THE CP-ODD NUCLEON INTERACTION AND THE VALUE OF T-VIOLATION IN NUCLEI*

Vladimir P. Gudkov

School of Physics

University of Melbourne

Parkville, Vic. 3052 Australia

Abstract

The relations between the value of T- and P-violating correlations in neutron scattering and different models of CP violation are discussed. It is shown that a specific structure of CP-odd nucleon interactions gives the possibility to obtain the essential information about CP-odd interaction at the quark-gluon level from nuclear experimental data. The up-to-date estimations for CP-violating nucleon coupling constants show that CP violation in neutron scattering is sensitive to many models of CP violation.

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I. INTRODUCTION

From the first experimental discovery of CP violation in the K^0 -meson decays in 1964 still there are no other experimental confirmation of CP violation in other systems in spite of many attempts in high energy, nuclear and atomic physics. The problem of CP violation is closely related to the time reversal invariance because, according to the CPT theorem, the violation of CP-invariance means the violation of time reversal invariance (T violation). Moreover, in low energy physics T violation is the only one possibility of manifestation of CP violation. It should be noted, that T violation has never been observed and, therefore, it is a subject of a special interest regardless of the CP violation itself. The problem of T violation has been a subject of an experimental investigation in nuclear physics for several tens years. In general, there are two different possibilities for T- violation: due to CP-odd and P-odd (or T- and P-violating) interactions or due to T-violating P-even interactions. The first case is related to the one observed in K - meson decays, and the second one – to phenomenological interactions which may not exist at all. Here we consider the first case. For the simplicity of terminology and in accordance to the common believe in the CPT theorem we use terms CP violation and T violation as synonyms. This does not restrict an idea about possible source of T violation and all conclusions are independent on a nature of T violation with one exception: calculations of CP violating nucleon coupling constants will be done CP- and P-violating interactions.

Investigations of T violation in resonance neutron scattering give the possibility to improve drastically the current situation in searching for T violation (see, e.g. paper [1] and references therein). As it has been shown [2], the main advantage in searching for CP violation in neutron scattering is a large expected value for CP-odd effects due to nuclear enhancement factors. The expected large value of nuclear effects might be a big disadvantage, also. A good illustration for such a situation is the well known large parity violation in neutron induced reactions where the complexity of the system leads to impossibility for a theoretical description of P-odd effects in nuclei in terms of quark-gluon weak interac-

tions. Therefore, P-odd effects are used to study the nuclear structure rather than the weak interactions which can be studied better in high energy physics.

Such a situation can not be satisfactory for the CP violation. Since the source of CP violation is still unknown, the primary aim is to find any manifestation of CP violation and to measure its intensity in terms of quark-gluon coupling constants to choose the appropriate mechanism of CP violation. For this purpose one must go from the experimental data in neutron scattering up to quark-gluon coupling constants and to solve the problem of theoretical description of the nuclear experimental data in terms of parameters of CP-violating models. The problem of a reliable interpretation of the experimental data is even more important for the improving of the current experimental restrictions on the CP-violating coupling constants if CP violating effects will be not detected in experiments.

To calculate various CP violating effects in nuclei we need go through the different levels of theoretical models. At first, one needs to obtain the effective low energy CP violating Lagrangian at the quark level for the particular model of CP violation. The second step is the calculation of the CP-violating nucleon-nucleon interaction using the obtained low energy Lagrangian. The third step is the calculation of nuclear CP-violating effects in a nuclear model using calculated CP-violating nucleon couplings. Each step of these calculations is a model dependent, in general.

For example, in order to describe the standard P-odd and CP-even nucleon-nucleon interaction it is necessary to calculate at least six different meson-nucleon coupling constants [3–5]. The masses, spin and isospin properties of these mesons are different from each other. Therefore, the obtained P-odd nucleon potential is rather complex and, being used in nuclear models, it leads to big uncertainties in calculations of P-odd nuclear effects.

It will be shown that the problem of interpretation of the CP-violating experimental data in neutron scattering might be solved successfully and one can get rid of the model dependencies at all levels of the calculation.

Let us recall the main results for the description of CP-violating effects in neutron scattering related to the T-odd and P-odd correlation $(\vec{\sigma}[\vec{k} \times \vec{l}])$, where $\vec{\sigma}$ and \vec{l} are neutron and

target spins, and \vec{k} is the neutron momentum. This correlation leads [6,7] to the difference of the total cross sections for the transmission of neutrons, polarized parallel and antiparallel to the axis $[\vec{k} \times \vec{I}]$, through the polarized target

$$\Delta\sigma_{CP} = \frac{4\pi}{k} \text{Im}(f_{\uparrow}^p - f_{\downarrow}^p), \quad (1)$$

and to the neutron spin rotation angle χ around the axis $[\vec{k} \times \vec{I}]$

$$\frac{d\chi}{dz} = \frac{2\pi N}{k} \text{Re}(f_{\uparrow}^p - f_{\downarrow}^p). \quad (2)$$

Here $f_{\uparrow,\downarrow}^p$ are the zero angle scattering amplitudes on the polarized nuclei for neutrons polarized parallel and antiparallel to the $[\vec{k} \times \vec{I}]$ axis, respectively, z is the target length, and N is the density of nuclei in the target.

It was shown [2,8] that T-violating parameters $\Delta\sigma_{CP}$ and $d\chi/dz$ look like the P-violating ones caused by the T-even P-odd correlation $(\vec{\sigma}\vec{k})$ and have the analogous enhancement factors which lead to their increase by a factor of $10^5 - 10^6$. Their expressions in the two resonances approximation are

$$\Delta\sigma_{CP} = -\frac{2\pi G_J}{k^2} \frac{w(\Gamma_s^n \Gamma_p^n(S))^{\frac{1}{2}}}{[s][p]} [(E - E_s)\Gamma_p + (E - E_p)\Gamma_s], \quad (3)$$

$$\frac{d\chi}{dz} = \frac{4\pi N G_J}{k^2} \frac{w(\Gamma_s^n \Gamma_p^n(S))^{\frac{1}{2}}}{[s][p]} [(E - E_s)(E - E_p) - \frac{1}{4}\Gamma_s \Gamma_p], \quad (4)$$

where $[s, p] = (E - E_{s,p})^2 + \Gamma_{s,p}^2/4$ and $E_{s,p}$, $\Gamma_{s,p}$ and $\Gamma_{s,p}^n$ are the energy, total and neutron widths of the s - and p -wave compound resonances, w is imaginary (T-non-invariant part) of the P-odd matrix element between these resonances, G_J is a spin function dependent on the spin of compound system J and the channel spin $S = I \pm 1/2$.

From eq.(3) and from the corresponding expression [8] for P-violating difference of the total cross sections for the transmission of neutrons with opposite helicities through an unpolarized target

$$\Delta\sigma_P \sim \frac{2\pi}{k^2} \frac{v(\Gamma_s^n \Gamma_p^n)^{\frac{1}{2}}}{[s][p]} [(E - E_s)\Gamma_p + (E - E_p)\Gamma_s] \quad (5)$$

one can obtain the relation between the values of the P-odd and the CP-odd effects [9]

$$\Delta\sigma_{CP} = \kappa(J) \frac{w}{v} \Delta\sigma_P, \quad (6)$$

where v is real part of the weak matrix element between the s - and p -resonance states. The parameter $\kappa(J)$ is

$$\kappa(I + 1/2) = -\frac{3}{2^{3/2}} \left(\frac{2I+1}{2I+3} \right)^{3/2} \left(\frac{3}{\sqrt{2I+3}} \gamma - \sqrt{I} \right)^{-1}, \quad (7)$$

$$\kappa(I - 1/2) = -\frac{3}{2^{3/2}} \left(\frac{2I+1}{2I-1} \right) \left(\frac{I}{I+1} \right)^{1/2} \left(-\frac{I-1}{\sqrt{2I-1}} \frac{1}{\gamma} + \sqrt{I+1} \right)^{-1}. \quad (8)$$

Here $\gamma = [\Gamma_p^n(I + 1/2)/\Gamma_p^n(I - 1/2)]^{1/2}$ is the ratio of the neutron width amplitudes for the different channel spins. In general, the parameter γ may be obtained from the angular correlation measurements in neutron induced reactions.

The P-odd parameter $\Delta\sigma_P$ has been measured in many experiments. Its relative value (compared with the neutron total cross section) in the vicinity of p-wave resonances has a huge magnitude for weak processes, up to 10^{-1} (see, e.g. ref. [10] and references therein).

From eq.(6) one can see that the measurement of the CP-odd and P-odd effects at the same p -wave compound resonance (when the values reach their maximum) leads to the possibility of extracting the ratio

$$< \lambda > = \frac{w}{v}. \quad (9)$$

Due to the large value of the P-odd parameter $\Delta\sigma_P$ in the vicinity of p-wave compound resonance, there is the possibility to measure the CP-odd parameter $< \lambda >$ at a level up to 10^{-4} (see, e.g. refs. [11,12]).

However, the parameter $< \lambda >$ is the ratio of the CP-odd to the P-odd matrix elements between s - and p -wave compound resonances, but not the ratio of nucleon (or quark) coupling constants. The structure of compound resonances is very complicated and is usually described by statistical methods. Therefore, we have a large experimental effect and can not obtain an information from the experimental result due to enormous difficulties in the

theoretical descriptions. The reasons for the enhancement and for the theoretical difficulties are the same - the complexity of nuclear compound states.

To avoid such deadlock we explore an approach where only ratios of CP-odd to P-odd parameters are calculated at all levels of a hierarchy of the models. If the possible structures of the CP-odd and P-odd interactions are known at each level (nuclear interactions, nucleon interactions and quark-gluon interactions) the calculations of the ratio for CP-odd to P-odd parameters give the opportunity to eliminate many model dependent features. The important point is that the experimental values of the P-odd parameters are known and their theoretical values have been calculated. It will be shown that the structure of CP-odd nucleon interactions is simpler than the structure of P-odd ones. This fact gives an additional simplification in obtaining of the CP-odd coupling constants from the nuclear experimental data.

Let us start from the consideration of the ratio of the compound nuclear matrix elements $\langle \lambda \rangle$.

II. THE RELATION BETWEEN NUCLEAR MATRIX ELEMENTS AND NUCLEON COUPLING CONSTANTS

To estimate the parameter $\langle \lambda \rangle$ we can use a simple model of the one particle interaction. Then the one particle potentials for P-violating [13] and CP-violating [14] interactions are:

$$V_P = \frac{G_F}{8^{1/2}M} \{(\vec{\sigma}\vec{p}), \rho(\vec{r})\}_+, \quad (10a)$$

$$V_{CP} = \frac{iG_F\lambda}{8^{1/2}M} \{(\vec{\sigma}\vec{p}), \rho(\vec{r})\}_-, \quad (10b)$$

where G_F is the weak interaction Fermi constant, M is the proton mass, $\rho(\vec{r})$ is the nucleon density, \vec{p} is the momentum of the valence nucleon and λ is the ratio of CP-violating to P-violating nucleon - nucleon coupling constants.

Now one obtains from eqs.(9) and (10) that

$$\langle \lambda \rangle = \frac{\lambda}{1 + 2\xi}, \quad (11)$$

where

$$\xi = \frac{\langle \phi_p | \rho(\vec{\sigma}\vec{p}) | \phi_s \rangle}{\langle \phi_p | (\vec{\sigma}\vec{p}) \rho | \phi_s \rangle}. \quad (12)$$

Here $\phi_{s,p}$ are the s, p -resonance wave functions of the compound nucleus.

Let us consider the matrix elements in eq.(12). The operator identity $2\vec{p} = iM[H, \vec{r}]$ leads to the value of the numerator [9]

$$\langle \phi_p | \rho(\vec{\sigma}\vec{p}) | \phi_s \rangle \simeq \frac{i\bar{\rho}M}{2} D_{sp} \langle \phi_p | (\vec{\sigma}\vec{r}) | \phi_s \rangle. \quad (13)$$

Here H is the single particle nuclear Hamiltonian, D_{sp} is the average single particle level spacing, and $\bar{\rho}$ is the average value of the nuclear density. The denominator of eq.(12) is

$$\begin{aligned} \langle \phi_p | (\vec{\sigma}\vec{p}) \rho | \phi_s \rangle &= -\langle \phi_p | (\vec{\sigma}\vec{r}) \frac{1}{r} \frac{\partial \rho}{\partial r} | \phi_s \rangle \\ &= \frac{2i\rho}{R^2} \langle \phi_p | (\vec{\sigma}\vec{r}) | \phi_s \rangle, \end{aligned} \quad (14)$$

where R is the nuclear radius.

Inserting eqs.(13) and (14) into eq.(12) we obtain

$$\xi = \frac{1}{4} M D_{sp} R^2 = \frac{1}{4} \pi (KR), \quad (15)$$

where we used the estimate of D_{sp} for the square-well potential case [15]:

$$D_{sp} = \frac{1}{MR^2} \pi KR, \quad (16)$$

and K is the nucleon momentum in the nucleus. Eq.(15) gives the numerical values for $\xi \in (1 \div 7)$. Therefore, we can conclude that the values of the matrix elements in eq.(12) are of the same order of magnitude and that, consequently, the values of $\langle \lambda \rangle$ and λ are of the same order of magnitude, as well. In other words, there are no large suppression factors in the relation between $\langle \lambda \rangle$ and λ parameters and, therefore, models of CP violation

might lead to measurable values of CP-violating effects in neutron scattering. Also, we arrive at the possibility to distinguish between the models of CP violation, which have different CP-odd nucleon-nucleon coupling constants. It should be noted, that when the experimental data will be available, the ratio $\langle \lambda \rangle / \lambda$ should be calculated more accurately for each particular nucleus using a realistic approximation for the nuclear density and wave functions.

If we consider the eq.(11) not as a rough approximation for the given above estimation of the ratio of the matrix elements but rather more seriously, we will come to the conclusion that the CP-odd matrix elements have a regular suppression factor $(1 + 2\xi)$ comparing to the P-odd ones. This result is in a good agreement with the detailed numerical studies (see, e.g. refs. [16,17]). Furthermore, neglecting the first term in the denominator of eq.(11) one has got the parametrical suppression factor [18] for CP-odd matrix elements

$$\frac{\langle \lambda \rangle}{\lambda} \simeq \frac{2}{\pi} K^{-1} r_0^{-1} A^{-1/3} \sim A^{-1/3}, \quad (17)$$

where $R = r_0 A^{1/3}$ and A is the atomic number. The existence of this possible suppression factor can be explained by the fact that [19] the CP-odd nuclear potential has the well-defined surface character and, therefore, it is proportional to the size of nuclear surface ($4\pi R^2 \sim A^{2/3}$), but the P-odd nuclear potential has the volume character and it is proportional to the nuclear volume ($\frac{4\pi}{3} R^3 \sim A$).

III. THE CP-ODD NUCLEON COUPLING CONSTANTS

To obtain a relation between the experimental data and the possible models of CP violation it is necessary to calculate the CP-odd nucleon coupling constants in these models. It is well known from the experience of calculations of P-odd nuclear interactions that this is a very difficult and sometimes an ambiguous procedure. To calculate P-odd nucleon interactions the following common problems have to be solved:

- to choose a model for description of nucleon-nucleon interactions;

- to calculate an effective symmetry violating Lagrangian, taking into account quark-gluon interactions at short distances, and to renormalize the Lagrangian to the nucleon scale;
- to calculate meson-nucleon P-odd interactions using hadron models.

The one-boson exchange model is usually used to describe nucleon-nucleon interactions. The π -, ρ -, and ω -meson exchanges are taking into account. The effective weak Lagrangian is calculated on the base of the standard model with QCD gluonic corrections at the short distances. The procedure of renormalization to the large distances (the nucleon scale) leads to the expression of the Lagrangian as a sum of terms with an accuracy up to $O(\alpha_s \ln(M_W^2/\mu^2))$, where α_s is a strong coupling constant, M_W is the mass of W -boson and μ is the parameter of the hadronic scale. It should be noted, that the QCD perturbation theory is not applicable at the hadronic scale ($\mu \sim 1\text{GeV}$), therefore, the renormalization procedure up to the level μ is not correct and might be a source of uncertainties in the further calculations. However, the source causing most uncertainties is the last step: the calculation of P-odd meson - nucleon coupling constants using hadron models.

Let us shortly overview some of the existing approaches for these calculations which are based on: quark models, topological soliton models, the chiral perturbation theory and QCD sum rules.

In the traditional approach using the quark model (see, for example [3–5]) the M -meson nucleon weak matrix element $\langle MN' | \mathcal{L}_{PV} | N \rangle$ might be represented as a sum of two parts:

$$h_M = \langle MN' | \mathcal{L}_{PV} | N \rangle = h_M^F + h_M^{NF}, \quad (18)$$

where h_M^F is so called "factorized" or calculable in the factorization approach part and h_M^{NF} is the " non-factorized" part; \mathcal{L}_{PV} is the effective weak Lagrangian. The factorized part of the matrix element for the case of π -mesons

$$h_\pi^F \sim \langle \pi^- | \bar{d}\gamma_5 u | 0 \rangle \cdot \langle p | \bar{u}d | n \rangle, \quad (19)$$

can be calculated using equations of motion for the quarks

$$\langle \pi^- | \bar{d} \gamma_5 u | 0 \rangle = \frac{f_\pi \cdot m_\pi^2}{(m_u + m_d)}, \quad (20)$$

$$\langle p | \bar{u} d | n \rangle = \frac{M_\Xi - 3M_\Lambda + 2M_p}{m_u - m_s}. \quad (21)$$

For the case of vector mesons (ρ, ω) , the vector meson dominance hypothesis is used for calculating of the vector current matrix element in the factorized part

$$h_\rho^F \sim \langle \rho | V_\mu | 0 \rangle \cdot \langle N' | A^\mu | N \rangle. \quad (22)$$

The non-factorized part h_M^{NF} can be calculated only numerically (e.g., in a quark bag model), therefore, it is the main source of uncertainties in these calculations. These uncertainties lead to a rather large range for the value of the weak π -meson coupling [3–5]: $h_\pi \in (1 \div 5) \cdot 10^{-7}$.

The topological soliton model approach has been used in last years [20,21] to calculate π -meson weak coupling constants. Its advantage is the possibility of simultaneous calculations of the strong and weak interaction regions. However, it does not predict all nucleon properties and, therefore, its accuracy and reliability does not look satisfactory enough. In this approach nucleons are considered as solitons of a non-linear meson theory. The Hamiltonian of weak interaction is rewriting in terms of currents constructed from meson fields, which make up the soliton. The meson field is represented as a sum of two components: one, that makes up the soliton and another, which is a small pionic fluctuation. The linear in the pionic fluctuation terms correspond to π -meson nucleon interactions and the quantalization of the respective operator gives the coupling constant in the following form [21]

$$h_\pi = 8\pi \frac{G_F \sin^2 \Theta_W}{\Theta \cdot f_\pi} \int_0^\infty r^2 [I_0(r) V_0(r) - \frac{2}{3} I_1(r) V_1(r)] dr, \quad (23)$$

where Θ_W is the Weinberg angle, Θ is the moment of inertia of the spinning soliton, $I_{0,1}(r)$ and $V_{0,1}(r)$ are the radial functions associated with the time (space) components of the isoscalar (isovector) soliton current, respectively. This expression gives the numerical value $h_\pi \sim 0.25 \cdot 10^{-7}$.

The chiral perturbation theory approach to weak nucleon interactions [22] gives the low energy weak meson-nucleon Hamiltonian which includes large $\pi\pi NN$ and $\gamma\pi NN$ couplings. However, in this approach the meson-nucleon coupling constants can be calculated only numerically, using lattice methods. The dimensional analysis used in ref. [22] gives the following π -meson nucleon coupling constant

$$h_\pi \simeq \left(\frac{\Lambda_\chi}{f_\pi} \right) \cdot \frac{G_F}{\sqrt{2}} \cdot f_\pi^2 \simeq 5 \cdot 10^{-7}. \quad (24)$$

It should be noted, that in the chiral approach the strange quarks give a large contribution to the weak coupling constants (see, paper [22] and references therein).

The QCD sum rules applied for the calculation of weak π -meson coupling constants [23,24] give a rather different results: $h_\pi \sim 5 \cdot 10^{-7}$ in the ref. [23] and $h_\pi \sim 0.3 \cdot 10^{-7}$ in the ref. [24]. As it has been stated in the last paper, the smaller result is obtained due to the cancellation between perturbative and non-perturbative QCD modifications of the weak process.

From the given consideration of different approaches for the calculation of P-odd meson-nucleon coupling constants we can see that this is a rather difficult problem which is still far from the final resolution. These difficulties are common for the calculations of both the P-odd and the CP-odd coupling constants, but in the case of CP violation an additional complexities exist: there are many various possible models for CP violation. Fortunately, the large number of these models leads to a few different structures for CP-violating low energy Lagrangians. Moreover, it will be shown that many of the existing problems for calculations of P-odd interactions can be simplified or even eliminated for calculations of CP-odd interactions if we calculate not the coupling constants themselves but the ratio of them to the P-odd coupling constants with the same (or, almost the same) structure of the effective Lagrangians. This approach gives a real advantage in eliminating some model dependant uncertainties arising from the strong interactions at the quark-gluon and nucleon levels. The next simplification is the fact [25], that to calculate the CP-odd nucleon interactions it is enough to take into account only π -meson contributions. Therefore, we

can use only the one π -meson - nucleon interaction to calculate all CP violating effects in nuclei. This is a very important point to be considered here (see ref. [25]).

For the low energy region all CP violating models can be grouped into four classes according to the sources of CP violation on the quark-gluon level:

- a. Complex quark mass matrices. In the mass eigenstate basis, there will be CP violation in the charged current due to exchange of gauge particles. One of the best known example is the Kobayashi-Maskawa model [26].
- b. Complex mixing angles for gauge bosons. An example is the left-right symmetric model [27].
- c. Complex vacuum expectation values of Higgs bosons, for example the Weinberg model [28].
- d. CP-odd pure gluonic interaction, and as the θ -term in QCD [29].

In a specific process, some or all of these CP violating sources contribute and corresponding effective Lagrangians include CP-odd pure quark, quark-gluon and pure gluonic operators. The pure quark operators appear in the form current \times current due to gauge boson exchange, or pseudo-scalar \times scalar structure due to scalar boson exchange. The most important feature of these Lagrangians is the presence of the right-current \times left-current or the pseudo-scalar \times scalar structures. These operators have enhanced contributions to the CP-odd pseudo-scalar meson-nucleon couplings. This is a principal difference compared to the structure of the P-odd and CP-even effective Lagrangian which leads to the enhancement of pseudo-scalar \times scalar contribution and, as a consequence, to decreasing the number of meson-nucleon coupling to just one π -meson interaction with nucleon.

Let us consider the low energy effective Lagrangian involving only u and d quarks (operators up to dimension six are considered). Exchanging gauge bosons at the tree level in the a- and b-type of models will produce the following structure of the Lagrangian

$$\begin{aligned}\mathcal{L} &\sim L \times L + L \times R + R \times L + R \times R \\ &= C_{LL}O_{LL} + C_{LR}O_{LR} + C_{RL}O_{RL} + C_{RR}O_{RR} ,\end{aligned}\tag{25}$$

where $O_{LL} = \bar{u}_L \gamma_\mu d_L \bar{d}_L \gamma_\mu u_L$ and other operators are defined in a similar way. Note that only $L \times R$ and $R \times L$ have CP violating interaction.

At the tree level the c-type of models will lead to the CP violating effective Lagrangian

$$\mathcal{L} \sim S \times P = C_{SP} \bar{q}_1 q_2 \bar{q}_3 \gamma_5 q_4 + h.c. ,\tag{26}$$

where q_i can be u and d quarks depending whether a charged or neutral scalar is exchanged to produce the effective Lagrangian.

The $L \times R$ term also contains a term proportional to $S \times P$. This can be seen by making a Fierz transformation on O_{LR} . We have

$$O_{LR}^F = -2\left[\frac{1}{3}\bar{u}_L u_R \bar{d}_R d_L + \frac{1}{2}\bar{u}_L \lambda^a u_R \bar{d}_R \lambda^a d_L\right] + h.c. .\tag{27}$$

We can now calculate the CP-odd meson-nucleon coupling constants for π^- - and ρ^- - mesons from the $L \times R$ term. Using the factorization approximation and the vector meson dominance hypothesis, we have

$$\begin{aligned}\bar{g}_{\pi^- NN} &\approx \langle \pi^- p | L \times R | n \rangle_{CP} = i \frac{Im C_{LR}}{2} \langle \pi^- | \bar{d} \gamma_\mu \gamma_5 u | 0 \rangle \langle p | \bar{u} \gamma_\mu d | n \rangle \\ &= i \frac{Im C_{LR}}{2} \frac{m_d^2 - m_u^2}{m_\pi^2} \langle \pi^- | \bar{d} \gamma_5 u | 0 \rangle \langle p | \bar{u} d | n \rangle , \\ \bar{g}_{\rho^- NN} &\approx \langle \rho^- p | L \times R | n \rangle_{CP} = \frac{Im C_{LR}}{2} \frac{m_\rho^2}{f_\rho} g_A .\end{aligned}\tag{28}$$

where m_ρ and f_ρ are the mass and strong form factor for ρ -meson with $f_\rho^2/4\pi \approx 2$, g_A is the nucleon axial form factor, m_u and m_d are masses of u - and d - quarks. Using the Fierz transformed operator O_{LR}^F and the factorization approximation, we obtain

$$\bar{g}_{\pi^0 NN} \approx \frac{1}{3} Im C_{LR} (\langle \pi^0 | \bar{d} \gamma_5 d | 0 \rangle \langle N | \bar{u} u | N \rangle - \langle \pi^0 | \bar{u} \gamma_5 u | 0 \rangle \langle N | \bar{d} d | N \rangle) .\tag{29}$$

From the above equation we clearly see that there is a suppression factor $(m_d^2 - m_u^2)/m_\pi^2$ for $\bar{g}_{\pi^- NN}$ compared with $\bar{g}_{\pi^0 NN}$.

To compare the contributions from the π and ρ meson exchanges to the CP-odd nucleon potential we remind that for the standard P-odd and CP-even interaction $L \times L$, we have the same structure of the corresponding coupling constants

$$\begin{aligned} g_{\pi^- NN}^p &\approx \frac{C_{LL}}{2} \frac{m_d^2 - m_u^2}{m_\pi^2} \langle \pi^- | \bar{d} \gamma_5 u | 0 \rangle \langle p | \bar{u} d | n \rangle . \\ g_{\rho NN}^p &\approx \frac{C_{LL}}{2} \frac{m_\rho^2}{f_\rho} g_A . \end{aligned} \quad (30)$$

It is well known that for the P-odd and CP-even nucleon potential the contributions from the π and ρ mesons have the same order of magnitude if the relative strength of the couplings is given by eq.(30) [3]. It is expected that the same thing should happen for the CP-odd nucleon potential. Then from eq.(28) we can see that the contributions from the ρ and π^- meson exchanges to the CP-odd potential will have the same order of magnitude. Therefore, we conclude that the dominant contribution to the CP-odd nucleon potential is from the π^0 meson exchange.

The similar results have been obtained [25] for the c-type of models. In this case, the ρ -meson nucleon coupling will be much smaller than π -meson nucleon couplings for the same reason as given above. However, unlike the situation in the a- and b- type of models where the π^0 meson-nucleon coupling is much larger than the π^- meson-nucleon coupling, the charged and neutral pion-nucleon coupling can be of the same order of magnitude. Therefore π^\pm and π^0 exchange can all make significant contributions to the CP-odd nucleon potential. The reason for this enhancement on $\bar{g}_{\pi NN}$ is due to the large contribution of the pseudo-scalar and scalar quark densities in the local approximation. A similar enhancement factor for the strange quark current has been found in penguin induced K-meson decays [30].

CP-odd pure gluonic operators ($J^{PC} = 0^{-+}$) can be generated in many models [31,32], particularly in the c- and d-type of models. It is interesting to note, that because of the pseudo-scalar nature of the operators, the pseudo-scalar meson-nucleon coupling constants are much bigger than the vector meson-nucleon coupling constants, just as they are for the pure quark operators. The estimation [25] of the ratio of the coupling constants for pseudo-scalar and vector mesons leads to the conclusion that for gluonic CP-odd operators

the coupling constant of the pseudo-scalar meson to nucleon is larger by about one order of magnitude than the vector meson-nucleon coupling constant. The same result is valid for the lowest order CP-odd quark-gluon operator (the colour-electric dipole moment) $\hat{O} = \bar{q}\sigma_{\mu\nu}\gamma_5(\lambda^a/2)qG^{a\mu\nu}$.

Now we can see that for all types of CP-violating models the contributions to the CP-violating nucleon-nucleon interaction from pseudo-scalar mesons are larger than the contributions from vector meson by about one order of magnitude. Therefore, the dominant CP violating nucleon-nucleon interaction in the one meson exchange approximation is from the π -meson exchange and to calculate CP-odd effects in nuclei with a reasonable accuracy, we need only consider pseudo-scalar meson exchange. (The dominant CP-odd π -meson contribution has been confirmed by numerical calculations in paper [33].) The situation here is quite different from the P-odd and CP-even nucleon potential, where the π , ρ and ω all contribute significantly.

IV. ESTIMATIONS OF CP-ODD NUCLEON INTERACTIONS FOR DIFFERENT MODELS

Let us estimate the parameter λ (the ration of CP-odd to P-odd nucleon coupling constants) for some models of CP violation. We will keep to the model classification given in the previous section.

A. Models of class (a).

The well known model of CP violation due to complex quark mass matrix is the standard Kobayashi-Maskawa (KM) model [26]. It gives negligible contribution to the nucleon CP-odd interaction [34,35]:

$$\lambda_{KM} \leq 10^{-10}.$$

Two other models with the similar source of CP violation are left- right [27] and horizontal [36] models. The corresponding parameters λ_{LR}^q and λ_H have been calculated in paper [37]. The comparison of effective low energy Lagrangians for that models with the Lagrangian for the Kobayashi-Maskawa model leads to the following expressions:

$$\lambda_{LR}^q \sim \lambda_{KM} \left(\frac{M_L}{M_R} \right)^2 \frac{\sin(\delta_2 - \delta_1)}{c_2 s_2 s_3 \sin \delta}, \quad (31)$$

$$\lambda_H \sim \lambda_{KM} \frac{4G_H \sin \phi}{G c_2 s_1 s_2 s_3 \sin \delta}. \quad (32)$$

Here $M_{L,R}$ are left(right)-handed gauge boson masses; δ is a CP-odd phase in the Kobayashi-Maskawa model and the $\delta_{1,2}$ are corresponding phases in the left- right model; $c_i = \cos \theta_i$, $s_i = \sin \theta_i$, where the θ_i are KM matrix mixing angles; G_H and ϕ are the strength and CP-odd phase of the horizontal interaction.

From eq.(31) it is obvious that the left-right model contribution in the given scenario (Class (a)) is very small $\lambda_{LR}^q \leq \lambda_{KM}$. Accepting the value for the strength of the horizontal interaction [36] ($10^{-16} GeV^{-2} \leq G_H \leq 10^{-11} GeV^{-2}$), we have got the same conclusion for the horizontal model contribution: $\lambda_H \leq \lambda_{KM}$. However, due to many uncertainties in the model, the case with the parameter $\lambda_H \leq 10^{-4}$ cannot be ruled out, too (see, e.g. ref. [38]).

It should be noted that the above estimations have been done for the standard case of three quark generations. However, in the presence of the fourth heavy quark generation the situation may be changed drastically. For example, in the Kobayashi-Maskawa model with four quark generations radiative electroweak corrections might lead to CP violation by several orders of magnitude larger than for the standard three generations case (see, e.g. calculations of the neutron electric dipole moment in ref. [39]).

B. Models of class (b).

The calculation of the CP violation due to complex mixing angles for gauge bosons in the left-right symmetric model gives [37]

$$\lambda_{LR}^W \sim 10 \sin \zeta \sin \alpha \simeq \frac{2\epsilon m_s}{43 m_c}, \quad (33)$$

where ζ and α are the CP-even and the CP-odd mixing phases of gauge bosons, ϵ is a CP-odd K -meson decay parameter, m_s and m_c are masses of s - and c -quarks¹. Using the experimental value for the K -meson decay parameter ϵ we get the value of $\lambda_{LR}^W \leq 10^{-6}$.

The other calculation [38] of the pion-nucleon CP-odd coupling constant in this model provides the more optimistic value $\lambda_{LR}^W \sim 4 \times 10^{-3}$. This result is directly dependant on the restriction on the CP-odd parameters of the model $|\zeta \sin(\alpha - \delta_2)| \leq 1.7 \times 10^{-3}$ obtained from an experiment on ^{19}Ne -decay [40]. However, the restriction on these parameters $|\zeta \sin(\alpha - \delta_2)| \leq 3 \times 10^{-6}$ obtained in paper [41] from the measurements of neutron electric dipole moment [42,43] ($|D_n| \leq 1.1 \times 10^{-25} e \cdot \text{cm}$) leads to the value $\lambda_{LR}^W \sim 10^{-7}$. It should be noted, that such a strong restriction on the CP-violating parameters in the left-right model has been obtained as a result of barring accidental cancellations in the QCD short-distance coefficient of the exchange diagram for the neutron dipole moment calculation [41]. However, these QCD corrections to the exchange diagram are very sensitive to the calculation approaches and to the long-distance QCD parameters.

C. Models of class (c).

The classical example of the CP violation due to complex vacuum expectation values of Higgs bosons is the Weinberg model of spontaneous CP- violation [28]. For this model it is convenient to estimate the parameter λ as the ratio of the CP-odd g_{CP} to P-odd g_P pion-nucleon coupling constants. We use the value of the $g_P \simeq 1.6 \times 10^{-7}$ (see ref. [5]). For CP violation from charged Higgs bosons exchange the effective CP-violating Lagrangian [44]

¹I appreciate Dr. P. Herczeg for the comment that the corresponding expression for λ_{LR}^W in ref. [37] has a superfluous factor $(M_L/M_R)^2$.

$$\mathcal{L}_{CP} = 2Im\{A\}m_um_d \cos^2\theta_c \times [(\bar{d}u)(\bar{u}i\gamma_5d) + (\bar{d}i\gamma_5u)(\bar{u}d)]. \quad (34)$$

leads [37] to

$$\begin{aligned} g_{CP}^{ch} &= \langle n\pi^+ | \mathcal{L}_{CP} | p \rangle \\ &\simeq Im\{A\} \frac{m_u - m_d}{m_u + m_d} m_\pi^2 f_\pi \frac{3M_\Lambda + M_\Sigma - 2M_P}{m_s - m_u} \cos^2\theta_c. \end{aligned} \quad (35)$$

Here m_π and f_π are pion mass and the decay constant, m_q is the quark mass, M_p and $M_{\Lambda,\Sigma}$ are proton and hyperon masses, and θ_c is the Cabibbo angle and A is the propagator of changed Higgs bosons.

For neutral Higgs bosons, the corresponding constant g_{CP}^0 can be written as [37]

$$g_{CP}^0 = g_s < \sigma H > < H | \pi > m_\pi^2, \quad (36)$$

where g_s is a scalar (σ) Higgs boson-nucleon coupling constant, $< H | \pi >$ is the pseudoscalar (H) Higgs boson-pion mixing amplitude, and $< \sigma H >$ is the neutral Higgs boson propagator.

Due to the anomaly in the energy-momentum tensor, the vertex g_s is proportional to the nucleon mass [45] M :

$$g_s = -8/29(M/v), \quad (37)$$

where $v = (G\sqrt{2})^{-1/2}$. If the "up"-quarks and "down"-quarks obtain their masses from different Higgs fields, then the expression for the pseudo-scalar Higgs boson and meson coupling is similar to the corresponding expression in the axion theory [46,47]:

$$< H | \pi > = \frac{f_\pi}{2\sqrt{2}v} \left[x \left(1 - N \frac{1-z}{1+z} \right) - \frac{1}{x} \left(1 + N \frac{1-z}{1+z} \right) \right]. \quad (38)$$

Here $z = m_u/m_d$, N is the number of quark generations, x is the ratio of the VEV's corresponding to "up"-and "down"-quark masses. Then, using these expressions with $x = 1$ and $N = 3$, we can obtain [37]

$$g_{CP}^0 = \frac{12\sqrt{2}}{29} \frac{< \sigma H >}{v^2} M f_\pi m_\pi^2 \frac{m_d - m_u}{m_d + m_u}. \quad (39)$$

The old estimations [44] of the propagator $Im\{A\} \simeq G \times 0.25 GeV^{-2}$ and an assumption that $\langle \sigma H \rangle / v^2 \simeq Im\{A\}$ gave very large parameters λ : for CP violation from charged Higgs bosons exchange $\lambda_H^{ch} \sim 10^{-4}$ and for CP violation from neutral Higgs bosons exchange $\lambda_H^0 \sim 10^{-1}$. The parameter λ_H^{ch} is proportional to m_H^{-2} (where m_H is a mass of charged Higgs boson) and the given value corresponds to a very small mass of Higgs boson $m_H \sim 2 GeV$. The given value for the parameter λ_H^0 is in a contradiction [46] with the restriction on neutron electric dipol moment. The up-to-date estimations give $\lambda_H^{ch} \leq 2 \times 10^{-6}$ and $\lambda_H^0 \leq 10^{-3}$.

D. Models of class (d).

The CP violation due to neutral Higgs boson exchange can be described in terms of pure gluonic operators. From this point of view the contribution from neutral Higgs bosons exchange discussed in the previous section corresponds to an effective dimension eight four gluonic operator $\sim GGG\tilde{G}$, where $\tilde{G}_{\mu\nu}^a = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G_{\rho\sigma}^a$. Indeed, the GG part of the operator corresponds to the scalar boson nucleon coupling and the $G\tilde{G}$ part corresponds to the pseudo scalar one in eq.(36). This operator is a dominant for an exchange of light Higgs bosons. In the case of a heavy Higgs bosons exchange ($m_H \geq 100 GeV$) the dominant operator is the dimension six pure gluonic CP- odd Weinberg operator $GG\tilde{G}$ [48]. The CP-odd Lagrangian for the Weinberg operator can be written as [49]

$$\mathcal{L} = \chi \times \eta_{QCD} \times \tilde{O}, \quad (40)$$

$$\tilde{O} = \frac{g_s^3}{(4\pi)^2} f_{abc} G_{\mu\nu}^a G_{\nu\rho}^b \tilde{G}_{\rho\mu}^c. \quad (41)$$

Here g_s is the QCD gauge coupling constant; η_{QCD} is the radiative QCD correction parameter; and χ is the dimension coefficient which can be calculated for specific CP- violating models. The parameter λ for that operator λ_G is calculated as the ration of CP-odd (g_{CP}) to P-odd (g_P) pseudo scalar meson - nucleon coupling constants. According to eq.(40), one can write

$$g_{CP} = \chi \times \eta_{QCD} \times M, \quad (42)$$

where $M = \langle Np | \tilde{O} | N \rangle$ is the nucleon-pseudo scalar meson matrix element for the \tilde{O} operator. Accepting the estimation [50] of this hadronic matrix element $M \sim 0.2 GeV$ and the value of P-odd pion-nucleon coupling constant [5] $g_P \simeq 1.6 \times 10^{-7}$, we get the parameter λ_G as:

$$\lambda_G \simeq 10^6 m_p^2 \chi \eta_{QCD}, \quad (43)$$

where m_p is the proton mass.

Using the calculations of the coefficient χ in paper [49], one can obtain the values for the parameter λ_G in different models of CP-violation. In the case of CP violation due to Higgs bosons exchange and under an assumption about the reasonable scale of the Higgs boson and t -quark masses ($2 \cdot m_H \sim m_t \sim 200 GeV$), one obtains [50]:

$$\lambda_{Higgs} \sim (0.2 - 1.0) \times 10^{-2} ImZ, \quad (44)$$

where Z is Higgs mixing parameter. Taking into account the bound on the parameter $ImZ \leq 0.03$ (which was obtained [49] from the experimental limit on the NEDM) one has

$$\lambda_{Higgs} \leq 3 \times 10^{-4}. \quad (45)$$

It should be noted, that the left-right model also can lead to the CP-odd three gluonic operator due to complex CP-odd mixing of left and right bosons. In this case, for the model with equal gauge coupling constants for the right and left bosons and when $M_R \gg M_L$ (where $M_{R(L)}$ is a mass of the right (left) boson) one obtains (see, also ref. [49,51])

$$\lambda_{LR} \sim 0.1 \sin \alpha \sin \xi. \quad (46)$$

Here ξ and α are a CP-even and a CP-odd mixing angles of the left and right bosons. The result for the parameter λ is dependent on the restriction on the parameters $(\sin \alpha \sin \xi)$ and leads to the following values : $\lambda_{LR} \leq 2 \cdot 10^{-4}$ or $\lambda_{LR} \leq 4 \cdot 10^{-7}$ (see discussion at the end of section "Model of Class (b)").

It should be noted, that the contribution from the Kobayashi - Maskawa model through the Weinberg three gluonic operator is almost negligible [49]. This is a consequence of the three loop contribution to the coefficient χ which leads to the suppression factor $\sim (m_b/M_W)^4$.

In the same way, one can calculate the value of λ for the θ -term in QCD using the CP-odd pion-nucleon coupling constant which was obtained in paper [29]. The experimental restriction on the neutron electric dipole moment leads to the following restriction on the parameter λ_θ :

$$\lambda_\theta \leq 5 \times 10^{-5}. \quad (47)$$

Taking into account that an accuracy for the existing calculations of the P-odd and CP-even nucleon coupling constants and the P-odd and CP-odd ones is about of one order of magnitude, the expected accuracy for the parameter λ is approximately at the same level. It means that a model with a rather large value of the parameter λ (for example, $\lambda \sim 10^{-2}$) might exist in each class of CP-violating models. It should be noted, that in spite of this conclusion the well known models of CP violation give a rather small value of the $\lambda \leq 10^{-3}$ (see the above discussions).

The given calculations of the parameter λ lead to the conclusion that in every class of CP-violating models the parameter λ might be large enough to be measured in the neutron scattering experiment. To improve the current restrictions on the λ the further theoretical investigations are needed.

V. THE IN-MEDIUM BEHAVIOR OF CP-ODD COUPLING CONSTANTS

The CP-violating coupling constants calculated in vacuum provide correct results in nuclear matter for almost all models because we are interested in the parameter λ , which is the ratio of the CP-odd to the P-odd nucleon coupling constants. If the origin of CP violation is not related to the strong interaction, this ratio for nuclear matter must be the

same as for the vacuum free particle interaction. From this point of view, the model of CP violation due to the θ -term in QCD Lagrangian is a rather special case because the mechanism of CP violation is related to the properties of the strong interaction. Therefore, the relative value of CP-odd effects in nuclear matter may be changed in comparison to the vacuum case. This problem has been considered in paper [52]. Since the measure of CP violation in vacuum due to the θ -term in QCD is [53]:

$$\kappa_{vac} = \frac{\langle \frac{\alpha_s}{\pi} G\tilde{G} \rangle_{vac}}{\langle \frac{\alpha_s}{\pi} GG \rangle_{vac}}, \quad (48)$$

the measure for the CP violation in nuclear matter is

$$\kappa_\rho = \frac{\langle \frac{\alpha_s}{\pi} G\tilde{G} \rangle_\rho}{\langle \frac{\alpha_s}{\pi} GG \rangle_\rho}. \quad (49)$$

Here $\langle \frac{\alpha_s}{\pi} GG \rangle_{vac}$ is a vacuum gluon condensate, $\langle \frac{\alpha_s}{\pi} G\tilde{G} \rangle_{vac}$ is a condensate of CP-odd gluonic operator $\frac{\alpha_s}{\pi} G\tilde{G}$ in the vacuum and $\langle \rangle_\rho$ are the corresponding in-medium condensates. From this expression one can see that a renormalization of CP-odd effects in nuclear matter is defined by the renormalization of the CP-odd operator $\langle \frac{\alpha_s}{\pi} G\tilde{G} \rangle_\rho$, because the gluon condensate is just slightly changed in nuclear matter at the saturation density [54].

The nuclear density dependence for the operator $\langle \frac{\alpha_s}{\pi} G\tilde{G} \rangle$ [52]

$$\frac{\langle \frac{\alpha_s}{\pi} G\tilde{G} \rangle_\rho}{\langle \frac{\alpha_s}{\pi} G\tilde{G} \rangle_{vac}} \simeq 1 + \frac{\rho}{\langle \bar{q}q \rangle_{vac}} \frac{\sigma_N}{(m_u + m_d)} \frac{(m_u + m_d)^2}{4m_u m_d} \quad (50)$$

is the same one as for the quark condensate [54]

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_{vac}} \simeq 1 + \frac{\rho}{\langle \bar{q}q \rangle_{vac}} \frac{\sigma_N}{(m_u + m_d)}. \quad (51)$$

Here ρ is the medium (nuclear matter) density; σ_N is the nucleon σ -term; $m_{u,d}$ are current masses of u, d -quarks. The additional multiplier in eq.(50) is not significant: $(m_u + m_d)^2/(4m_u m_d) = 1.08$. Taking into account that the quark condensate may be reduced in its value by about (25% – 50%) at the nuclear saturation density [54], one can conclude that the CP-odd interaction due to θ -term has the in-medium reduction.

The CP-odd coupling constant g_{CP} is proportional to the measure of CP violation κ_ρ and, consequently, has the same density dependence as the quark condensates (by neglecting the

gluon condensate density dependence). From the other hand, the P-odd coupling constant g_P is, also, proportional to the quark condensate value (see, e.g. ref. [5]). Therefore, the parameter $\lambda = g_{CP}/g_P$ has a negligible density dependence.

It should be emphasized that the approximation used for description of the quark condensates behavior in nuclear matter [54] has an accuracy of about 10% up to the nuclear saturation density. Therefore, the above conclusion is valid to the same accuracy.

VI. CP-ODD NUCLEON POTENTIAL

For the estimations of nuclear matrix elements in section 2 we used simple one particle nuclear potentials. To calculate the parameter λ for real experiments it is desirable to use CP-odd one boson exchange potentials. Since the π -meson contribution is dominant for the CP-odd one boson exchange interactions [25], the following one meson CP-odd potential [55,38]

$$\begin{aligned}
V_{CP}^{\pi} = & -\frac{m_{\pi}^2}{8\pi m_N} g_{\pi NN} \cdot \vec{r} \frac{e^{-m_{\pi}r}}{m_{\pi}r^2} \left[1 + \frac{1}{m_{\pi}r}\right] \\
& \times [\bar{g}_{\pi NN}^{(0)} \cdot (\vec{\tau}_1 \cdot \vec{\tau}_2) \cdot (\vec{\sigma}_1 - \vec{\sigma}_2) \\
& + \frac{\bar{g}_{\pi NN}^{(1)}}{2} \cdot [(\tau_{1z} + \tau_{2z}) \cdot (\vec{\sigma}_1 - \vec{\sigma}_2) + (\tau_{1z} - \tau_{2z}) \cdot (\vec{\sigma}_1 + \vec{\sigma}_2)] \\
& + \bar{g}_{\pi NN}^{(2)} \cdot (3\tau_{1z}\tau_{2z} - \vec{\tau}_1 \cdot \vec{\tau}_2) \cdot (\vec{\sigma}_1 - \vec{\sigma}_2)]
\end{aligned} \tag{52}$$

is a good approximation for the description of CP violation in nuclei. Here g and $\bar{g}^{(T)}$ are strong CP-even and weak CP-odd pion-nucleon coupling constants; $T = 0, 1, 2$ correspond to isoscalar, isovector and isotensor interactions, respectively; $\vec{\sigma}$ and $\vec{\tau}$ are the spin and isospin of the nucleon.

Therefore, to calculate CP-violating effects in nuclei in terms of the one boson nucleon interactions one can use only π -meson nucleon CP-odd parameters $\bar{g}^{(T)}$. The simple structure of the CP-odd nucleon potential gives the opportunity to calculate CP-violating effects and leads to the simple parameterization of all CP-odd effects in nuclei using only π -meson parameters. This fact provides the opportunity to test different models of CP violation with

a good accuracy in the framework of the given parameterization.

It should be noted, that different models of CP violation usually give contributions not to all three parameters $\bar{g}^{(T)}$, but rather to some of them. Therefore, the real potential for the particular model is usually even much simpler than the one given in eq.(52).

VII. CONCLUSIONS

The study of T-violating correlations in neutron scattering leads to a unique opportunity to search for CP violation because of the large enhancement of experimental CP-odd effects in the vicinity of p-wave resonances and the possibility to calculate CP-odd nuclear effects starting from the original model of CP violation at the quark-gluon level. The estimated CP-violating effects for some models show that each class of CP-violating models can give a measurable effect for the neutron scattering experiments. Even if CP violation will not be detected in the neutron scattering experiments, the obtained experimental data could give the unambiguous restrictions on many models of CP violation. Since the nucleon CP-odd potential has the main contribution from one π -meson exchange it is possible to obtain a direct relation between CP-odd nuclear effects and the value of the neutron electric dipole moment if the one meson loop gives the main contribution [29,56,57].

Therefore, the results which can be obtained from the neutron scattering experiments might be of the same accuracy and importance as, for example, the results to be expected from the currently fashionable B-meson physics or from a measurement of the neutron electric dipole moment.

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